

# Functional Integral Approach in the Theory of Color Superconductivity<sup>1</sup>

**Nguyen Van Hieu**

*Institute of Physics, NCST of Vietnam*

and

*Faculty of Technology, Vietnam National University, Hanoi*

## Abstract

In this series of lectures we present the functional integral method for studying the superconducting pairing of quarks with the formation of the diquarks as well as the quark-antiquark pairing in dense QCD. The dynamical equations for the superconducting order parameters are the nonlinear integral equations for the composite quantum fields describing the quark-quark or quark-antiquark systems. These composite fields are the bi-local fields if the pairing is generated by the gluon exchange while for the instanton induced pairing interactions they are the local ones. The expressions of the free energy densities are derived. The binding of three quarks is also discussed.

## 1 Introduction

The superconducting pairing of quarks due to the gluon exchange in QCD with the formation of the diquark condensate was proposed by Barrois<sup>[1]</sup> and Frautschi<sup>[2]</sup> since more than two decades and then studied by Bailin and Love<sup>[3]</sup>, Donoglu and Sateesh<sup>[4]</sup>, Iwasaki and Iwado<sup>[5]</sup>. Recently, in a series of papers by Alford, Rajagopal and Wilczek<sup>[6]</sup>, Schäfer and Wilczek<sup>[7]</sup>, Rapp, Schäfer, Shuryak and Velkovsky<sup>[8]</sup>, Evans, Hsu and Schwetz<sup>[9]</sup>, Son<sup>[10]</sup>, Carter and Diakonov<sup>[11]</sup> and others<sup>[12–21]</sup> there arose a new interest to the existence of the diquark Bose condensate in the QCD dense matter—the color superconductivity. The connection between the color superconductivity and the chiral phase transition in QCD was studied by Berges and Rajagopal<sup>[22]</sup>, Harada and Shibata<sup>[23]</sup>. There exists also the spontaneous parity violation, as it was shown by Pisarski and Rischke<sup>[24]</sup>.

For the study of many-body systems of relativistic particles with the internal degrees of freedom as well as with the virtual creation and annihilation of the particle-antiparticle pairs the functional integral technique is a powerful mathematical tool. This method was applied to the study of the color superconductivity as well as the quark-antiquark pairing<sup>[25–28]</sup>.

In this series of lectures we present the basics of the functional integral method for the study of the color superconductivity in QCD at finite temperature and density (the so-called dense QCD or thermal QCD). As the physical origin of the superconducting pairing of quarks we consider two different commonly discussed mechanisms: the direct local four-fermion interactions of the quark field and the quark-quark non-local interaction due to the gluon exchange. The direct four-quark interaction might be induced by the instantons<sup>[11,12]</sup>.

We follow the general method of the functional integral approach in the theory of superconductivity<sup>[29,30]</sup>. We start from the expressions of the partition functions of the systems of interacting quarks and antiquarks with some local or non-local quark-quark interactions. Then we introduce the local or bi-local composite fields describing the diquarks or quark-antiquark pairs, establish the effective action of these composite fields and derive their field equations. The order parameters of the ground state of the diquark or quark-antiquark condensate are the expectation

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<sup>1</sup>Lectures at the VIth International School in Theoretical Physics, Vung Tau 27 December 1999–08 January 2000.

values of the composite fields in the corresponding state of the system. Due to the translational invariance of the ground state these expectation values are coordinate-independent (for the local fields) or depend only on the difference of the coordinates (for the bi-local ones). The equations for the order parameters are the special cases of the field equations. The expressions of the free energy density in the corresponding phases are also derived.

We work in the imaginary time formalism and write briefly

$$x = (\mathbf{x}, \tau), \quad \int dx = \int_0^\beta d\tau \int d\mathbf{x}, \quad \beta = \frac{1}{kT},$$

$k$  is the Boltzmann constant and  $T$  is the temperature. We denote  $\psi_A$ ,  $\bar{\psi}^A$  the quark field and its Dirac conjugate, where  $A = (\alpha, a, i)$  is the set consisting of the Dirac spinor index  $\alpha = 1, 2, 3, 4$ , the flavor index  $i = 1, 2, 3, \dots, N_f$  and the color one  $a = 1, 2, 3, \dots, N_c$ . The internal symmetry groups are assumed to be  $SU(N_f)_f$  and  $SU(N_c)_c$ . The partition function of the system of free quarks and antiquarks with the chemical potential  $\mu$  and at the temperature  $T$  can be expressed in the form of the functional integral

$$Z_0 = \int [D\psi] [D\bar{\psi}] \exp \left\{ - \int dx \bar{\psi}^A(x) L_A^B \psi_B(x) \right\} \quad (1)$$

where

$$L_A^B = \delta_a^b \delta_j^j \left[ \gamma_4 \left( \frac{\partial}{\partial \tau} - \mu \right) + \boldsymbol{\gamma} \nabla + M \right]_\alpha^\beta, \quad (2)$$

and  $M$  is the bare quark mass.

Introduce the generating functional

$$\begin{aligned} Z_0[\eta, \bar{\eta}] &= \int [D\psi] [D\bar{\psi}] \exp \left\{ - \int dx \bar{\psi}^A(x) L_A^B \psi_B(x) \right\} \\ &\quad \exp \left\{ - \int dx [\bar{\eta}^A(x) \psi_A(x) + \bar{\psi}^A(x) \eta_A(x)] \right\} \end{aligned} \quad (3)$$

with anti-commuting parameters  $\eta_A(x)$  and  $\bar{\eta}^A(x)$ . The  $2n$ -point Green functions are expressed in terms of the functional derivatives of  $Z_0[\eta, \bar{\eta}]$  at the special value  $\eta_A(x) = \bar{\eta}^A(x) = 0$ :

$$\begin{aligned} G_{A_1, \dots, A_n}^{B_1, \dots, B_n}(x_1, x_2, \dots, x_n; y_1, y_2, \dots, y_n) &= \\ &= \left\langle T \left\{ \psi_{A_1}(x_1) \psi_{A_2}(x_2) \dots \psi_{A_n}(x_n) \bar{\psi}^{B_n}(y_n) \dots \bar{\psi}^{B_2}(y_2) \bar{\psi}^{B_1}(y_1) \right\} \right\rangle \\ &= (-1)^n \frac{1}{Z_0} \frac{\delta^{2n} Z_0[\eta, \bar{\eta}]}{\delta \bar{\eta}^{A_1}(x_1) \dots \delta \bar{\eta}^{A_n}(x_n) \delta \eta_{B_n}(y_n) \dots \delta \eta_{B_1}(y_1)} |_{\eta=\bar{\eta}=0}. \end{aligned} \quad (4)$$

In particular

$$\begin{aligned} G_A^B(x; y) &= G_A^B(x - y) = \left\langle T \left\{ \psi_A(x) \bar{\psi}^B(y) \right\} \right\rangle \\ &= -\frac{1}{Z_0} \frac{\delta^2 Z_0[\eta, \bar{\eta}]}{\delta \bar{\eta}^A(x) \delta \eta_B(y)} |_{\eta=\bar{\eta}=0}. \end{aligned} \quad (5)$$

Denote

$$\begin{aligned} S_A^B(x - y) &= \delta_a^b \delta_i^j S_\alpha^\beta(x - y) = \delta_a^b \delta_i^j S_\alpha^\beta(\mathbf{x} - \mathbf{y}, \tau - \sigma), \\ S_\alpha^\beta(\mathbf{x} - \mathbf{y}, \tau - \sigma) &= S_{\alpha\beta}(\mathbf{x} - \mathbf{y}, \tau - \sigma) \end{aligned} \quad (6)$$

the solution of the equation

$$L_A^B S_B^C(x-y) = \delta_A^C \delta(x-y), \quad (7)$$

$$x = (\mathbf{x}, \tau), \quad y = (\mathbf{y}, \sigma), \quad \delta(x-y) = \delta(\mathbf{x}-\mathbf{y}) \delta(\tau-\sigma),$$

$$\left[ \gamma_4 \left( \frac{\partial}{\partial \tau} - \mu \right) + \boldsymbol{\gamma} \nabla + M \right]_{\alpha\beta} S_{\beta\gamma}(\mathbf{x}-\mathbf{y}, \tau-\sigma) = \delta_{\alpha\gamma} \delta(\mathbf{x}-\mathbf{y}) \delta(\tau-\sigma). \quad (8)$$

Shifting the functional integration variables

$$\begin{aligned} \psi_B(x) &\rightarrow \psi_B(x) + \int dy S_B^D(x-y) \eta_D(y), \\ \bar{\psi}^A(x) &\rightarrow \bar{\psi}^A(x) + \int dz \bar{\eta}^C(z) S_C^A(z-x) \end{aligned}$$

in the r.h.s. of the formula (1), we derive the explicit expression of the generating functional (3)

$$Z_0[\eta, \bar{\eta}] = Z_0 \exp \left\{ \int dx \int dy \bar{\eta}^A(x) S_A^B(x-y) \eta_B(y) \right\}. \quad (9)$$

Substituting this expression into the r.h.s. of the formula (5), we obtain the two-point Green function

$$G_A^B(x-y) = \left\langle T \left\{ \psi_A(x) \bar{\psi}^B(y) \right\} \right\rangle = S_A^B(x-y). \quad (10)$$

Similarly, from the formulae (4) and (9) it follows the Wick theorem for the  $2n$ -point Green functions of the free fermionic fields.

Introduce the Fourier transform  $\tilde{S}_{\alpha\beta}(p) = \tilde{S}_{\alpha\beta}(\mathbf{p}, \varepsilon_m)$  of  $S_{\alpha\beta}(x) = S_{\alpha\beta}(\mathbf{x}, \tau)$ :

$$\begin{aligned} S_{\alpha\beta}(\mathbf{x}, \tau) &= \frac{1}{\beta} \sum_m e^{i\varepsilon_m t} \frac{1}{(2\pi)^3} \int d\mathbf{p} e^{i\mathbf{p}\mathbf{x}} \tilde{S}_{\alpha\beta}(\mathbf{p}, \varepsilon_m) \\ \varepsilon_m &= (2m+1) \frac{\pi}{2}, \end{aligned} \quad (11)$$

$m$  being the integers  $m = 0, \pm 1, \pm 2, \dots$ . From the equation (8) it follows that

$$\tilde{S}_{\alpha\beta}(p) = \left( \frac{1}{ip + M} \right)_{\alpha\beta} = \frac{(-ip + M)_{\alpha\beta}}{p^2 + M} \quad (12)$$

with the notations

$$\hat{p} = (\varepsilon_m + i\mu) \gamma_4 + \boldsymbol{\gamma} \mathbf{p}, \quad p^2 = (\varepsilon_m + i\mu)^2 + \mathbf{p}^2. \quad (13)$$

In the calculations we shall use also the expression of  $\tilde{S}_{\alpha\beta}(-p) = \tilde{S}_{\alpha\beta}(-\mathbf{p}, -\varepsilon_m)$ . For the convenience we write it in the form

$$\tilde{S}_{\alpha\beta}(-p) = \left( \frac{1}{-ip' + M} \right)_{\alpha\beta} = \frac{(ip' + M)_{\alpha\beta}}{p'^2 + M}, \quad (14)$$

where

$$\hat{p}' = (\varepsilon_m - i\mu) \gamma_4 + \boldsymbol{\gamma} \mathbf{p}, \quad p'^2 = (\varepsilon_m - i\mu)^2 + \mathbf{p}^2. \quad (15)$$

To study the color superconductivity we consider the quark-quark pairing in QCD with the formation of the diquark condensate. Then we investigate the quark-antiquark pairing. The corresponding composite fields are the meson ones. We discuss also the possibility to extend our reasonings to the study of the binding of three quarks. The composite particles in this case are the baryons.

## 2 Quark-Quark Pairing

For the simplicity in writing the formulae we begin our study by considering the superconducting quark-quark pairing due to some direct four-fermion coupling of quarks with the interaction Lagrangian

$$\begin{aligned} L_{int} &= \frac{1}{2} \bar{\psi}^A(x) \bar{\psi}^C(x) V_{CA}^{BD} \psi_D(x) \psi_B(x), \\ V_{AC}^{BD} &= V_{CA}^{DB} = -V_{CA}^{BD} = -V_{AC}^{DB}. \end{aligned} \quad (16)$$

The partition function of the system equals

$$\begin{aligned} Z &= \int [D\psi] [D\bar{\psi}] \exp \left\{ - \int dx \bar{\psi}^A(x) L_A^B \psi_B(x) \right\} \\ &\quad \cdot \exp \left\{ \frac{1}{2} \int dx \bar{\psi}^A(x) \bar{\psi}^C(x) V_{CA}^{BD} \psi_D(x) \psi_B(x) \right\}. \end{aligned} \quad (17)$$

Introduce the antisymmetric bi-spinor local fields  $\Phi_{CA}(x)$ ,  $\bar{\Phi}^{AC}(x)$

$$\bar{\Phi}^{CA}(x) = -\bar{\Phi}^{AC}(x), \Phi_{AC}(x) = -\Phi_{CA}(x), \quad (18)$$

and the functional integral

$$Z_0^\Phi = \int [D\Phi] [D\bar{\Phi}] \exp \left\{ -\frac{1}{2} \int dx \bar{\Phi}^{AC}(x) V_{CA}^{BD}(x-y) \Phi_{DB}(x) \right\}. \quad (19)$$

By shifting the functional integration variables

$$\begin{aligned} \Phi_{DB}(x) &\rightarrow \Phi_{DB}(x) + \psi_D(x) \psi_B(x), \\ \bar{\Phi}^{AC}(x) &\rightarrow \bar{\Phi}^{AC}(x) + \bar{\psi}^A(x) \bar{\psi}^C(x), \end{aligned}$$

we establish the Hubbard-Stratonovich transformation

$$\begin{aligned} &\exp \left\{ \frac{1}{2} \int dx \bar{\psi}^A(x) \bar{\psi}^C(x) V_{CA}^{BD} \psi_D(x) \psi_B(x) \right\} \\ &= \frac{1}{Z_0^\Phi} \int [D\Phi] [D\bar{\Phi}] \exp \left\{ -\frac{1}{2} \int dx \bar{\Phi}^{AC}(x) V_{CA}^{BD} \Phi_{DB}(x) \right\} \\ &\quad \exp \left\{ -\frac{1}{2} \int dx \left[ \bar{\Delta}^{BD}(x) \psi_D(x) \psi_B(x) + \bar{\psi}^A(x) \bar{\psi}^C(x) \Delta_{CA}(x) \right] \right\}, \end{aligned} \quad (20)$$

where

$$\bar{\Delta}^{BD}(x) = \bar{\Phi}^{AC}(x) V_{CA}^{BD}, \quad \Delta_{CA}(x) = V_{CA}^{BD} \Phi_{DB}(x), \quad (21)$$

$$\bar{\Delta}^{DB}(x) = -\bar{\Delta}^{BD}(x), \quad \Delta_{AC}(x) = -\Delta_{CA}(x), \quad (22)$$

and rewrite the partition function (17) in the form

$$Z = \frac{1}{Z_0^\Phi} \int [D\Phi] [D\bar{\Phi}] \exp \{ S_{\text{eff}} [\Phi, \bar{\Phi}] \} \quad (23)$$

with the effective action

$$S_{\text{eff}} [\Phi, \bar{\Phi}] = -\frac{1}{2} \int dx \bar{\Phi}^{BD}(x) V_{DB}^{AC} \Phi_{CA}(x) + W [\Delta, \bar{\Delta}], \quad (24)$$

$$\begin{aligned} &\exp \{ W [\Delta, \bar{\Delta}] \} = \\ &= 1 + \sum_{n=1}^{\infty} \Gamma^{(2n)} [\Delta, \bar{\Delta}] \\ &= \left\langle T \left[ \exp \left\{ -\frac{1}{2} \int dx \left[ \bar{\psi}^A(x) \bar{\psi}^C(x) \Delta_{CA}(x) + \bar{\Delta}^{BD}(x) \psi_D(x) \psi_B(x) \right] \right\} \right] \right\rangle. \end{aligned} \quad (25)$$

Calculations give

$$\begin{aligned}\Gamma^{(2)} [\Delta, \overline{\Delta}] &= W^{(2)} [\Delta, \overline{\Delta}] = \\ &= \frac{1}{2} \int dx_1 \int dx_2 \overline{\Delta}^{A_1 C_1}(x_1) S_{C_1}^{C_2}(x_1 - x_2) \Delta_{C_2 A_2}(x_2) S_{A_1}^{T A_2}(x_2 - x_1),\end{aligned}\quad (26)$$

$$\Gamma^{(4)} [\Delta, \overline{\Delta}] = \frac{1}{2!} \left( W^{(2)} [\Delta, \overline{\Delta}] \right)^2 + W^{(4)} [\Delta, \overline{\Delta}], \quad (27)$$

$$\begin{aligned}W^{(4)} [\Delta, \overline{\Delta}] &= -\frac{1}{4} \int dx_1 \dots \int dx_4 \overline{\Delta}^{A_1 C_1}(x_1) S_{C_1}^{C_2}(x_1 - x_2) \Delta_{C_2 A_2}(x_2) S_{A_3}^{T A_2}(x_2 - x_3) \\ &\quad \overline{\Delta}^{A_3 C_3}(x_3) S_{C_3}^{C_4}(x_3 - x_4) \Delta_{C_4 A_4}(x_4) S_{A_1}^{T A_4}(x_4 - x_1),\end{aligned}\quad (28)$$

$$\Gamma^{(6)} [\Delta, \overline{\Delta}] = \frac{1}{3!} \left( W^{(2)} [\Delta, \overline{\Delta}] \right)^3 + W^{(2)} [\Delta, \overline{\Delta}] W^{(4)} [\Delta, \overline{\Delta}] + W^{(6)} [\Delta, \overline{\Delta}], \quad (29)$$

$$\begin{aligned}W^{(6)} [\Delta, \overline{\Delta}] &= \frac{1}{6} \int dx_1 \dots \int dx_6 \overline{\Delta}^{A_1 C_1}(x_1) S_{C_1}^{C_2}(x_1 - x_2) \Delta_{C_2 A_2}(x_2) S_{A_3}^{T A_2}(x_2 - x_3) \\ &\quad \dots \overline{\Delta}^{A_5 C_5}(x_5) S_{C_3}^{C_4}(x_5 - x_6) \Delta_{C_6 A_6}(x_6) S_{A_1}^{T A_6}(x_6 - x_1),\end{aligned}\quad (30)$$

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with

$$S_B^{TA}(x_1 - x_2) = S_B^A(x_2 - x_1).$$

We have then

$$W [\Delta, \overline{\Delta}] = \sum_{n=1}^{\infty} W^{(2n)} [\Delta, \overline{\Delta}]. \quad (31)$$

From the variational principle for the effective action we derive the field equation

$$\frac{1}{2} \Delta_{CA}(x) = V_{CA}^{BD} \sum_{n=1}^{\infty} \frac{\delta W^{(2n)} [\Delta, \overline{\Delta}]}{\delta \overline{\Delta}^{BD}(x)}. \quad (32)$$

Using the explicit expressions of  $W^{(2n)} [\Delta, \overline{\Delta}]$ , we obtain

$$\begin{aligned}\Delta_{CA}(x) &= V_{CA}^{BD} \left\{ \int dx_2 S_D^{C_2}(x - x_2) \Delta_{C_2 A_2}(x_2) S_B^{T A_2}(x_2 - x) \right. \\ &\quad - \int dx_2 \dots \int dx_4 S_D^{C_2}(x - x_2) \Delta_{C_2 A_2}(x_2) S_{A_3}^{T A_2}(x_2 - x_3) \\ &\quad \overline{\Delta}^{A_3 C_3}(x_3) S_{C_3}^{C_4}(x_3 - x_4) \Delta_{C_4 A_4}(x_4) S_B^{T A_4}(x_4 - x) \\ &\quad + \int dx_2 \dots \int dx_6 S_D^{C_2}(x - x_2) \Delta_{C_2 A_2}(x_2) S_{A_3}^{T A_2}(x_2 - x_3) \\ &\quad \overline{\Delta}^{A_3 C_3}(x_3) S_{C_3}^{C_4}(x_3 - x_4) \dots \Delta_{C_6 A_6}(x_6) S_B^{T A_6}(x_6 - x) \\ &\quad \left. - \dots \right\}.\end{aligned}\quad (33)$$

In the special class of the constant solutions

$$\Delta_{CA}(x) = \Delta_{CA} = V_{CA}^{BD} \Phi_{DB}, \quad \overline{\Delta}^{BD}(x) = \overline{\Delta}^{BD} = \overline{\Phi}^{AC} V_{CA}^{BD}, \quad (34)$$

we have the extended BCS gap equation

$$\begin{aligned}\Delta_{CA} &= V_{CA}^{BD} \frac{1}{\beta} \sum_m \frac{1}{(2\pi)^3} \int d\mathbf{p} \\ &\quad \left[ \widetilde{S}(\mathbf{p}, \varepsilon_m) \Delta \widetilde{S}^T(-\mathbf{p}, -\varepsilon_m) \frac{1}{1 + \overline{\Delta} \widetilde{S}(\mathbf{p}, \varepsilon_m) \Delta \widetilde{S}^T(-\mathbf{p}, -\varepsilon_m)} \right]_{DB},\end{aligned}\quad (35)$$

where  $\tilde{S}(\mathbf{p}, \varepsilon_m)$ ,  $\tilde{S}^T(-\mathbf{p}, -\varepsilon_m)$ ,  $\Delta$  and  $\overline{\Delta}$  are the matrices with the elements  $\tilde{S}_A^B(\mathbf{p}, \varepsilon_m)$ ,  $\tilde{S}_A^{TB}(-\mathbf{p}, -\varepsilon_m)$ ,  $\Delta_{CA}$ , and  $\overline{\Delta}^{AC}$

At the values of the superconducting order parameters  $\Delta_{CA}$  and  $\overline{\Delta}^{BD}$  satisfying the extended BCS gap equation the effective action equals

$$\begin{aligned} S_{\text{eff}}[\Phi, \overline{\Phi}] = & \left( \frac{1}{2} - \frac{1}{4} \right) \int dx_1 \dots \int dx_4 \text{Tr} [\overline{\Delta} S(x_1 - x_2) \Delta S^T(x_2 - x_3) \right. \\ & \quad \left. \overline{\Delta} S(x_3 - x_4) \Delta S^T(x_4 - x_1)] \right. \\ & - \left( \frac{1}{2} - \frac{1}{6} \right) \int dx_1 \dots \int dx_6 \text{Tr} [\overline{\Delta} S(x_1 - x_2) \Delta S^T(x_2 - x_3) \right. \\ & \quad \left. \dots \overline{\Delta} S(x_5 - x_6) \Delta S^T(x_6 - x_1)] \right. \\ & + \dots \end{aligned} \quad (36)$$

Denote  $F[\mathbf{x}; \Delta]$  the free energy density of the condensate. The effective action is expressed in terms of this free energy density in the following manner

$$S_{\text{eff}}[\Phi, \overline{\Phi}] = -\beta \int d\mathbf{x} F[\mathbf{x}; \Delta]. \quad (37)$$

Comparing (36) with (37), we obtain

$$\begin{aligned} F[\mathbf{x}; \Delta] = F[\Delta] = & -\frac{1}{\beta} \sum_m \frac{1}{(2\pi)^3} \int d\mathbf{p} \\ & \text{Tr} \left\{ \left( \frac{1}{2} - \frac{1}{4} \right) [\overline{\Delta} \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta \tilde{S}^T(-\mathbf{p}, -\varepsilon_m)]^2 \right. \\ & - \left( \frac{1}{2} - \frac{1}{6} \right) [\overline{\Delta} \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta \tilde{S}^T(-\mathbf{p}, -\varepsilon_m)]^3 \\ & \left. + \left( \frac{1}{2} - \frac{1}{8} \right) [\overline{\Delta} \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta \tilde{S}^T(-\mathbf{p}, -\varepsilon_m)]^4 - \dots \right\}. \end{aligned} \quad (38)$$

Summing up the infinite series, we write the r.h.s of the formula (38) in the compact form

$$\begin{aligned} F[\mathbf{x}; \Delta] = & \frac{1}{\beta} \sum_m \frac{1}{(2\pi)^3} \int d\mathbf{p} \frac{1}{2} \text{Tr} \left[ \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta \tilde{S}^T(-\mathbf{p}, -\varepsilon_m) \overline{\Delta} \right. \\ & \left\{ \frac{1}{1 + \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta \tilde{S}^T(-\mathbf{p}, -\varepsilon_m) \overline{\Delta}} \right. \\ & \left. - \int_0^1 d\alpha \frac{1}{1 + \alpha \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta \tilde{S}^T(-\mathbf{p}, -\varepsilon_m) \overline{\Delta}} \right\} \left. \right]. \end{aligned} \quad (39)$$

Let us discuss the general form of the superconducting order parameters. Consider first the constants  $\Delta_{AC}$ . We have

$$\Delta_{AC} = \Delta_{(ai\alpha)(ck\gamma)} = (\gamma_5 C)_{\alpha\gamma} \Delta_{(ai)(ck)}^S + (C)_{\alpha\gamma} \Delta_{(ai)(ck)}^P, \quad (40)$$

where  $\Delta_{(ai)(ck)}^S$  are the scalar constants while the  $\Delta_{(ai)(ck)}^P$  are the pseudoscalar ones. If the parity is conserved, then all pseudoscalar constants  $\Delta_{(ai)(ck)}^P$  must be zero. The existence of non-vanishing pseudoscalar constants  $\Delta_{(ai)(ck)}^P$  would signify the spontaneous breaking of the parity conservation. Because of the condition (22) the constants  $\Delta_{(ai)(ck)}^S$  and  $\Delta_{(ai)(ck)}^P$  must have the property

$$\Delta_{(ck)(ai)}^S = \Delta_{(ai)(ck)}^S, \quad \Delta_{(ck)(ai)}^P = \Delta_{(ai)(ck)}^P. \quad (41)$$

This means, in particular, that if they are symmetric (antisymmetric) with respect to the flavor indices  $i$  and  $j$ , they must be also symmetric (antisymmetric) with respect to the color ones  $a$  and  $b$ .

For the study of the quark-quark pairing due to the gluon exchange we start from the partition function in the form

$$Z = \int [D\psi][D\bar{\psi}] \exp \left\{ - \int dx \bar{\psi}^A(x) L_A^B \psi_B(x) \right. \\ \left. \cdot \exp \left\{ \frac{1}{2} \int dx \int dy \bar{\psi}^A(x) \bar{\psi}^C(y) V_{CA}^{BD}(x-y) \psi_D(y) \psi_B(x) \right\} \right\}, \quad (42)$$

where

$$V_{CA}^{BD}(x-y) = -\frac{g^2}{2\pi^2} \sum_I (\gamma_\mu \otimes \lambda_I)_A^B (\gamma_\mu \otimes \lambda_I)_C^D \frac{1}{(x-y)^2}, \\ (\gamma_\mu \otimes \lambda_I)_A^B = (\gamma_\mu)_\alpha^\beta (\lambda_I)_a^b \delta_i^j, \quad \sum_I (\lambda_I)_a^b (\lambda_I)_c^d = \frac{1}{2} \left[ \delta_c^b \delta_a^d - \frac{1}{N_c} \delta_a^b \delta_c^d \right]. \quad (43)$$

$\lambda_I$  are the Gell-Mann matrices of the color symmetry group. In order to describe the diquark systems we introduce some composite bi-local bi-spinor fields  $\Phi_{BD}(x, y)$ ,  $\bar{\Phi}^{AC}(x, y)$  obeying the Fermi-Dirac statistics

$$\Phi_{DB}(y, x) = -\Phi_{BD}(x, y), \quad \bar{\Phi}^{CA}(y, x) = -\bar{\Phi}^{AC}(x, y), \quad (44)$$

and the functional integral over these bosonic fields

$$Z_0^\Phi = \int [D\Phi] [D\bar{\Phi}] \exp \left\{ -\frac{1}{2} \int dx \int dy \bar{\Phi}^{AC}(x, y) V_{CA}^{BD}(x-y) \Phi_{DB}(y, x) \right\}. \quad (45)$$

By means the shift of the functional integration variables

$$\begin{aligned} \Phi_{DB}(y, x) &\rightarrow \Phi_{DB}(y, x) + \psi_D(y) \psi_B(x) \\ \bar{\Phi}^{AC}(x, y) &\rightarrow \bar{\Phi}^{AC}(x, y) + \bar{\psi}^A(x) \bar{\psi}^C(y), \end{aligned}$$

we can establish the Hubbard-Stratonovich transformation

$$\begin{aligned} &\exp \left\{ \frac{1}{2} \int dx \int dy \bar{\psi}^A(x) \bar{\psi}^C(y) V_{CA}^{BD}(x-y) \psi_D(y) \psi_B(x) \right\} \\ &= \frac{1}{Z_0^\Phi} \int [D\Phi] [D\bar{\Phi}] \exp \left\{ -\frac{1}{2} \int dx \int dy \bar{\Phi}^{AC}(x, y) V_{CA}^{BD}(x-y) \Phi_{DB}(y, x) \right\} \\ &\quad \exp \left\{ -\frac{1}{2} \int dx \int dy [\bar{\Delta}^{BD}(x, y) \psi_D(y) \psi_B(x) + \bar{\psi}^A(x) \bar{\psi}^C(y) \Delta_{CA}(y, x)] \right\}, \end{aligned} \quad (46)$$

$$\begin{aligned} \Delta_{CA}(y, x) &= V_{CA}^{BD}(x-y) \Phi_{DB}(y, x), \\ \bar{\Delta}^{BD}(x, y) &= \bar{\Phi}^{AC}(x, y) V_{CA}^{BD}(x-y), \end{aligned} \quad (47)$$

$$\Delta_{AC}(x, y) = -\Delta_{CA}(y, x), \quad \bar{\Delta}^{DB}(y, x) = -\bar{\Delta}^{BD}(x, y), \quad (48)$$

and rewrite the partition function

$$\begin{aligned} Z &= \frac{1}{Z_0^\Phi} \int [D\Phi] [D\bar{\Phi}] \exp \left\{ -\frac{1}{2} \int dx \int dy \bar{\Phi}^{AC}(x, y) V_{CA}^{BD}(x-y) \Phi_{DB}(y, x) \right\} \\ &\quad \int [D\psi] [D\bar{\psi}] \exp \left\{ - \int dx \bar{\psi}^A(x) L_A^B \psi_B(x) \right\} \\ &\quad \exp \left\{ -\frac{1}{2} \int dx \int dy [\bar{\Delta}^{BD}(x, y) \psi_D(y) \psi_B(x) + \bar{\psi}^A(x) \bar{\psi}^C(y) \Delta_{CA}(y, x)] \right\} \end{aligned} \quad (49)$$

in the form (23) with the effective action

$$S_{\text{eff}}[\Phi, \bar{\Phi}] = -\frac{1}{2} \int dx \int dy \bar{\Phi}^{AC}(x, y) V_{CA}^{BD}(x-y) \Phi_{DB}(y, x) + W[\Delta, \bar{\Delta}], \quad (50)$$

$$\begin{aligned}
& \exp \left\{ W [\Delta, \overline{\Delta}] \right\} = \\
= & 1 + \sum_{n=1}^{\infty} \Gamma^{(2n)} [\Delta, \overline{\Delta}] \\
= & \left\langle T \left[ \exp \left\{ -\frac{1}{2} \int dx \int dy \left[ \overline{\Delta}^{BD}(x, y) \psi_D(y) \psi_B(x) + \overline{\psi}^A(x) \overline{\psi}^C(y) \Delta_{CA}(y, x) \right] \right\} \right] \right\rangle. \tag{51}
\end{aligned}$$

Calculations give

$$\begin{aligned}
\Gamma^{(2)} [\Delta, \overline{\Delta}] = & W^{(2)} [\Delta, \overline{\Delta}] = \frac{1}{2} \int dx_1 \int dy_1 \int dx_2 \int dy_2 \\
& \overline{\Delta}^{A_1 C_1}(x_1, y_1) S_{C_1}^{C_2}(y_1 - y_2) \Delta_{C_2 A_2}(y_2, x_2) S_{A_1}^{T A_2}(x_2 - x_1), \tag{52}
\end{aligned}$$

$$S_{A_1}^{T A_2}(x_2 - x_1) = S_{A_1}^{A_2}(x_1 - x_2), \tag{53}$$

$$\Gamma^{(4)} [\Delta, \overline{\Delta}] = \frac{1}{2} \left( W^{(2)} [\Delta, \overline{\Delta}] \right)^2 + W^{(4)} [\Delta, \overline{\Delta}], \tag{54}$$

$$\begin{aligned}
W^{(4)} [\Delta, \overline{\Delta}] = & -\frac{1}{4} \int dx_1 \int dy_1 \int dx_2 \int dy_2 \int dx_3 \int dy_3 \int dx_4 \int dy_4 \\
& \overline{\Delta}^{A_1 C_1}(x_1, y_1) S_{C_1}^{C_2}(y_1 - y_2) \Delta_{C_2 A_2}(y_2, x_2) S_{A_3}^{T A_2}(x_2 - x_3) \tag{55} \\
& \overline{\Delta}^{A_3 C_3}(x_3, y_3) S_{C_3}^{C_4}(y_3 - y_4) \Delta_{C_4 A_4}(y_4, x_4) S_{A_1}^{T A_4}(x_4 - x_1),
\end{aligned}$$

$$\Gamma^{(6)} [\Delta, \overline{\Delta}] = \frac{1}{3!} \left( W^{(2)} [\Delta, \overline{\Delta}] \right)^3 + W^{(2)} [\Delta, \overline{\Delta}] W^{(4)} [\Delta, \overline{\Delta}] + W^{(6)} [\Delta, \overline{\Delta}], \tag{56}$$

$$\begin{aligned}
W^{(6)} [\Delta, \overline{\Delta}] = & \frac{1}{6} \int dx_1 \int dy_1 \int dx_2 \int dy_2 \dots \int dx_5 \int dy_5 \int dx_6 \int dy_6 \\
& \overline{\Delta}^{A_1 C_1}(x_1, y_1) S_{C_1}^{C_2}(y_1 - y_2) \Delta_{C_2 A_2}(y_2, x_2) S_{A_3}^{T A_2}(x_2 - x_3) \\
& \overline{\Delta}^{A_3 C_3}(x_3, y_3) S_{C_3}^{C_4}(y_3 - y_4) \Delta_{C_4 A_4}(y_4, x_4) S_{A_5}^{T A_4}(x_4 - x_5) \tag{57} \\
& \overline{\Delta}^{A_5 C_5}(x_5, y_5) S_{C_5}^{C_6}(y_5 - y_6) \Delta_{C_6 A_6}(y_6, x_6) S_{A_1}^{T A_6}(x_6 - x_1),
\end{aligned}$$

$$\begin{aligned}
\Gamma^{(8)} [\Delta, \overline{\Delta}] = & \frac{1}{4!} \left( W^{(2)} [\Delta, \overline{\Delta}] \right)^4 + \frac{1}{2} \left( W^{(2)} [\Delta, \overline{\Delta}] \right)^2 W^{(4)} [\Delta, \overline{\Delta}] \tag{58} \\
& + \frac{1}{2} \left( W^{(4)} [\Delta, \overline{\Delta}] \right)^2 + W^{(2)} [\Delta, \overline{\Delta}] W^{(6)} [\Delta, \overline{\Delta}] + W^{(8)} [\Delta, \overline{\Delta}],
\end{aligned}$$

$$\begin{aligned}
W^{(8)} [\Delta, \overline{\Delta}] = & -\frac{1}{8} \int dx_1 \int dy_1 \int dx_2 \int dy_2 \dots \int dx_7 \int dy_7 \int dx_8 \int dy_8 \\
& \overline{\Delta}^{A_1 C_1}(x_1, y_1) S_{C_1}^{C_2}(y_1 - y_2) \Delta_{C_2 A_2}(y_2, x_2) S_{A_3}^{T A_2}(x_2 - x_3) \\
& \overline{\Delta}^{A_3 C_3}(x_3, y_3) S_{C_3}^{C_4}(y_3 - y_4) \Delta_{C_4 A_4}(y_4, x_4) S_{A_5}^{T A_4}(x_4 - x_5) \tag{59} \\
& \overline{\Delta}^{A_5 C_5}(x_5, y_5) S_{C_5}^{C_6}(y_5 - y_6) \Delta_{C_6 A_6}(y_6, x_6) S_{A_7}^{T A_6}(x_6 - x_7) \\
& \overline{\Delta}^{A_7 C_7}(x_7, y_7) S_{C_7}^{C_8}(y_7 - y_8) \Delta_{C_8 A_8}(y_8, x_8) S_{A_1}^{T A_8}(x_8 - x_1), \\
& \dots
\end{aligned}$$

It is easy to verify that

$$W [\Delta, \overline{\Delta}] = \sum_{n=1}^{\infty} W^{(2n)} [\Delta, \overline{\Delta}]. \tag{60}$$

From the variational principle for the effective action we derive the field equation

$$\frac{1}{2}\Delta_{CA}(y, x) = V_{CA}^{BD}(x - y) \sum_{n=1}^{\infty} \frac{\delta W^{(2n)}[\Delta, \bar{\Delta}]}{\delta \bar{\Delta}^{BD}(x, y)}. \quad (61)$$

It has the explicit form

$$\begin{aligned} \Delta_{CA}(y, x) = & V_{CA}^{BD}(x - y) \left\{ \int dx_2 \int dy_2 S_D^{C_2}(y - y_2) \Delta_{C_2 A_2}(y_2, x_2) S_B^{T A_2}(x_2 - x) \right. \\ & - \int dx_2 \int dy_2 \dots \int dx_4 \int dy_4 S_D^{C_2}(y - y_2) \Delta_{C_2 A_2}(y_2, x_2) S_{A_3}^{T A_2}(x_2 - x_3) \\ & \quad \bar{\Delta}^{A_3 C_3}(x_3, y_3) S_{C_3}^{C_4}(y_3 - y_4) \Delta_{C_4 A_4}(y_4, x_4) S_B^{T A_4}(x_4 - x) \\ & + \int dx_2 \int dy_2 \dots \int dx_6 \int dy_6 S_D^{C_2}(y - y_2) \Delta_{C_2 A_2}(y_2, x_2) S_{A_3}^{T A_2}(x_2 - x_3) \\ & \quad \bar{\Delta}^{A_3 C_3}(x_3, y_3) S_{C_3}^{C_4}(y_3 - y_4) \Delta_{C_4 A_4}(y_4, x_4) S_{A_5}^{T A_4}(x_4 - x_5) \\ & \quad \bar{\Delta}^{A_5 C_5}(x_5, y_5) S_{C_5}^{C_6}(y_5 - y_6) \Delta_{C_6 A_6}(y_6, x_6) S_B^{T A_6}(x_6 - x) \\ & - \int dx_2 \int dy_2 \dots \int dx_8 \int dy_8 S_D^{C_2}(y - y_2) \Delta_{C_2 A_2}(y_2, x_2) S_{A_3}^{T A_2}(x_2 - x_3) \\ & \quad \dots \bar{\Delta}^{A_7 C_7}(x_7, y_7) S_{C_7}^{C_8}(y_7 - y_8) \Delta_{C_8 A_8}(y_8, x_8) S_B^{T A_8}(x_8 - x) \\ & \quad \left. + \dots \right\}. \end{aligned} \quad (62)$$

Considering the solutions of this equation in the special class of functions depending only on the difference of the coordinates

$$\Delta_{CA}(y, x) = \Delta_{CA}(y - x), \quad \bar{\Delta}^{BD}(x, y) = \bar{\Delta}^{BD}(x - y), \quad (63)$$

performing the Fourier transformations

$$\begin{aligned} \Delta_{CA}(\mathbf{y} - \mathbf{x}, \sigma - \tau) &= \frac{1}{\beta} \sum_m e^{i\varepsilon_m(\sigma - \tau)} \frac{1}{(2\pi)^3} \int d\mathbf{p} e^{i\mathbf{p}(\mathbf{y} - \mathbf{x})} \tilde{\Delta}_{CA}(\mathbf{p}, \varepsilon_m), \\ \bar{\Delta}^{BD}(\mathbf{x} - \mathbf{y}, \tau - \sigma) &= \frac{1}{\beta} \sum_m e^{i\varepsilon_m(\tau - \sigma)} \frac{1}{(2\pi)^3} \int d\mathbf{p} e^{i\mathbf{p}(\mathbf{x} - \mathbf{y})} \tilde{\bar{\Delta}}^{BD}(\mathbf{p}, \varepsilon_m), \quad (64) \\ V_{CA}^{DB}(\mathbf{x} - \mathbf{y}, \tau - \sigma) &= \frac{1}{\beta} \sum_m e^{i\omega_m(\sigma - \tau)} \frac{1}{(2\pi)^3} \int d\mathbf{p} e^{i\mathbf{p}(\mathbf{y} - \mathbf{x})} \tilde{V}_{CA}^{DB}(\mathbf{p}, \omega_m), \end{aligned}$$

$$\varepsilon = (2m + 1) \frac{\pi}{\beta}, \quad \omega_m = 2m \frac{\pi}{\beta},$$

and introducing matrices  $\tilde{\Delta}(\mathbf{p}, \varepsilon_m)$ ,  $\tilde{\bar{\Delta}}(\mathbf{p}, \varepsilon_m)$ ,  $\tilde{S}(\mathbf{p}, \varepsilon_m)$ ,  $\tilde{S}^T(-\mathbf{p}, -\varepsilon_m)$  with the elements  $\tilde{\Delta}_{CA}(\mathbf{p}, \varepsilon_m)$ ,  $\tilde{\bar{\Delta}}^{BD}(\mathbf{p}, \varepsilon_m)$ ,  $\tilde{S}_A^B(\mathbf{p}, \varepsilon_m)$ ,  $\tilde{S}_B^{TA}(-\mathbf{p}, -\varepsilon_m)$ , we derive the extended BCS gap equation for the superconducting quark-quark pairing in QCD

$$\begin{aligned} \tilde{\Delta}_{CA}(\mathbf{p}, \varepsilon_m) = & \frac{1}{\beta} \sum_n \frac{1}{(2\pi)^3} \int d\mathbf{q} \tilde{V}_{CA}^{BD}(\mathbf{p} - \mathbf{q}, \varepsilon_m - \varepsilon_n) \\ & \left[ \tilde{S}(\mathbf{q}, \varepsilon_n) \tilde{\Delta}(\mathbf{q}, \varepsilon_n) \tilde{S}^T(-\mathbf{q}, -\varepsilon_n) \right. \\ & \left. \frac{1}{1 + \tilde{\bar{\Delta}}(\mathbf{q}, \varepsilon_n) \tilde{S}(\mathbf{q}, \varepsilon_n) \tilde{\Delta}(\mathbf{q}, \varepsilon_n) \tilde{S}^T(-\mathbf{q}, -\varepsilon_n)} \right]_{DB}. \quad (65) \end{aligned}$$

At the values of the fields  $\Delta_{CA}(y, x)$  and  $\bar{\Delta}^{BD}(x, y)$  satisfying the equation (62) the effective action (50) equals

$$S_{eff}[\Phi, \bar{\Phi}] = W[\Delta, \bar{\Delta}] - \int dx \int dy \bar{\Delta}^{AC}(x, y) \frac{\delta W[\Delta, \bar{\Delta}]}{\delta \bar{\Delta}^{AC}(x, y)}$$

$$\begin{aligned}
&= - \left( \frac{1}{4} - \frac{1}{2} \right) \int dx_1 \int dy_1 \dots \int dx_4 \int dy_4 \text{Tr} [\overline{\Delta}(x_1, y_1) S(y_1 - y_2) \Delta(y_2, x_2) \\
&\quad S^T(x_2 - x_3) \overline{\Delta}(x_3, y_3) S(y_3 - y_4) \Delta(y_4, x_4) S^T(x_4 - x_1)] \\
&\quad + \left( \frac{1}{6} - \frac{1}{2} \right) \int dx_1 \int dy_1 \dots \int dx_6 \int dy_6 \text{Tr} [\overline{\Delta}(x_1, y_1) S(y_1 - y_2) \Delta(y_2, x_2) \\
&\quad S^T(x_2 - x_3) \dots \overline{\Delta}(x_5, y_5) S(y_5 - y_6) \Delta(y_6, x_6) S^T(x_6 - x_1)] \\
&\quad - \left( \frac{1}{8} - \frac{1}{2} \right) \int dx_1 \int dy_1 \dots \int dx_8 \int dy_8 \text{Tr} [\overline{\Delta}(x_1, y_1) S(y_1 - y_2) \Delta(y_2, x_2) \\
&\quad S^T(x_2 - x_3) \dots \overline{\Delta}(x_7, y_7) S(y_7 - y_8) \Delta(y_8, x_8) S^T(x_8 - x_1)] \\
&\quad + \dots, \tag{66}
\end{aligned}$$

where  $\Delta(y, x)$ ,  $\overline{\Delta}(y, x)$ ,  $S(x - y)$ ,  $S^T(x - y)$  denote the matrices with the elements  $\Delta_{CA}(y, x)$ ,  $\overline{\Delta}^{AC}(x, y)$ ,  $S_A^B(x - y)$ ,  $S_B^{TA}(x - y)$ . In the case of the special class (63) of the solutions  $\Delta_{CA}(y - x)$ ,  $\overline{\Delta}^{AC}(x - y)$  the effective action is expressed in terms of the free energy by means of the formula (37). Comparing the expressions (37) and (66) and performing the Fourier transformation, we obtain

$$\begin{aligned}
F[\mathbf{x}, \Delta] &= F[\Delta] = -\frac{1}{\beta} \sum_m \frac{1}{(2\pi)^3} \int d\mathbf{p} \\
&\quad \text{Tr} \left\{ \left( \frac{1}{2} - \frac{1}{4} \right) [\tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}(\mathbf{p}, \varepsilon_m) \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}^T(-\mathbf{p}, -\varepsilon_m)]^2 \right. \\
&\quad - \left( \frac{1}{2} - \frac{1}{6} \right) [\tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}(\mathbf{p}, \varepsilon_m) \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}^T(-\mathbf{p}, -\varepsilon_m)]^3 \\
&\quad + \left( \frac{1}{2} - \frac{1}{8} \right) [\tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}(\mathbf{p}, \varepsilon_m) \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}^T(-\mathbf{p}, -\varepsilon_m)]^4 \\
&\quad \dots \left. \dots \right\}. \tag{67}
\end{aligned}$$

This series can be also written in the compact form of the integral representation

$$\begin{aligned}
F[\Delta] &= \frac{1}{\beta} \sum_m \frac{1}{(2\pi)^3} \int d\mathbf{p} \frac{1}{2} \text{Tr} \left[ \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta(\mathbf{p}, \varepsilon_m) \tilde{S}^T(-\mathbf{p}, -\varepsilon_m) \overline{\Delta}(\mathbf{p}, \varepsilon_m) \right. \\
&\quad \left\{ \frac{1}{1 + \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta(\mathbf{p}, \varepsilon_m) \tilde{S}^T(-\mathbf{p}, -\varepsilon_m) \overline{\Delta}(\mathbf{p}, \varepsilon_m)} \right. \\
&\quad \left. - \int_0^1 d\alpha \frac{1}{1 + \alpha \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta(\mathbf{p}, \varepsilon_m) \tilde{S}^T(-\mathbf{p}, -\varepsilon_m) \overline{\Delta}(\mathbf{p}, \varepsilon_m)} \right\} \right]. \tag{68}
\end{aligned}$$

In order to simplify the expression for  $\Delta_{AC}(\mathbf{p}, \varepsilon_m)$  we introduce 4-vector  $p_\mu$  with the fourth component  $p_4 = \varepsilon_m$  and denote  $\Delta_{AC}(\mathbf{p}, \varepsilon_m)$  by  $\Delta_{AC}(p)$ . The condition (48) is now written in the form

$$\Delta_{BA}(-p) = -\Delta_{AB}(p). \tag{69}$$

The bi-spinors  $\Delta_{AB}(p)$  are expressed in terms of the Dirac bi-spinors

$$\begin{aligned}
\Delta_{AB}(p) &= \Delta_{(ai)\alpha(bj)\beta}(p) = (\gamma_5 C)_{\alpha\beta} \Delta_{(ai)(bj)}^S(p) + (C)_{\alpha\beta} \Delta_{(ai)(bj)}^P(p) \\
&\quad + (\gamma_\mu \gamma_5 C)_{\alpha\beta} \Delta_{\mu(ai)(bj)}^V(p) + (\gamma_\mu C)_{\alpha\beta} \Delta_{\mu(ai)(bj)}^A(p) \\
&\quad + (\sigma_{\mu\nu} \gamma_5 C)_{\alpha\beta} \Delta_{\mu\nu(ai)(bj)}^t(p).
\end{aligned} \tag{70}$$

From the conditions (69) it follows that under the interchange  $(ai) \leftrightarrow (bj)$  and the inversion  $p \rightarrow -p$  the scalar, pseudoscalar and vector functions are invariant while the pseudovector and tensor functions change their sign

$$\Delta_{(bj)(ai)}^{S,P}(-p) = \Delta_{(ai)(bj)}^{S,P}(p), \quad \Delta_{\mu(bj)(ai)}^V(-p) = \Delta_{\mu(ai)(bj)}^V(p), \tag{71}$$

$$\Delta_{\mu(bj)(ai)}^A(-p) = -\Delta_{\mu(ai)(bj)}^A(p), \quad \Delta_{\mu\nu(ai)(bj)}^t(-p) = -\Delta_{\mu\nu(bj)(ai)}^t(p).$$

In general, the existence of non-vanishing superconducting order parameters which are not the singlets of the color and/or flavor groups and lower the free energy would mean the spontaneous breaking of the color and/or flavor symmetries. For the systems with the isomorphic color and flavor groups  $SU(N)_c$  and  $SU(N)_f$  there may exist the superconducting order parameters which are the irreducible spinor representations of the groups  $SU(N)_c$  and  $SU(N)_f$  but the singlet of the "diagonal"  $SU(N)$  subgroup of the direct product  $SU(N)_c \otimes SU(N)_f$ . In this case we have the "color-flavor locking".

### 3 Quark-Antiquark Pairing.

The direct four-fermion coupling of the quark fields with the interaction Lagrangian (16) or the non-local interaction of the quark fields with the effective action given in the r.h.s of the formula (42) are also the origins of the quark-antiquark pairing. In the case of the quark-antiquark pairing due to the direct four-fermion coupling of the quark field we use the interaction Lagrangian in the form

$$\begin{aligned} L_{int} &= \frac{1}{2} \bar{\psi}^A(x) \psi_B(x) U_{AC}^{BD} \bar{\psi}^C(x) \psi_D(x), \\ U_{CA}^{DB} &= -U_{AC}^{BD} = -U_{CA}^{DB} = U_{AC}^{DB}, \end{aligned} \quad (72)$$

where instead of the constants  $V_{CA}^{BD}$  in (16) we use the new notations

$$U_{AC}^{BD} = V_{CA}^{BD}. \quad (73)$$

The partition function of the system equals

$$\begin{aligned} Z &= \int [D\psi] [D\bar{\psi}] \exp \left\{ - \int dx \bar{\psi}^A(x) L_A^B \psi_B(x) \right\} \\ &\quad \exp \left\{ \frac{1}{2} \int dx \bar{\psi}^A(x) \psi_B(x) U_{AC}^{BD} \bar{\psi}^C(x) \psi_D(x) \right\}. \end{aligned} \quad (74)$$

Introducing the local hermitian fields  $\Phi_A^B(x)$  and the functional integral

$$Z_0^\Phi = \int [D\Phi] \exp \left\{ - \frac{1}{2} \int dx \Phi_B^A(x) U_{AC}^{BD} \Phi_D^C(x) \right\}, \quad (75)$$

we establish the Hubbard-Stratonovich transformation

$$\begin{aligned} &\exp \left\{ \frac{1}{2} \int dx \bar{\psi}^A(x) \psi_B(x) U_{AC}^{BD} \bar{\psi}^C(x) \psi_D(x) \right\} = \\ &= \frac{1}{Z_0^\Phi} \int [D\Phi] \exp \left\{ - \frac{1}{2} \int dx \Phi_B^A(x) U_{AC}^{BD} \Phi_D^C(x) \right\} \\ &\quad \exp \left\{ - \int dx \bar{\psi}^A(x) \psi_B(x) \Delta_A^B(x) \right\}, \end{aligned} \quad (76)$$

$$\Delta_A^B(x) = U_{AC}^{BD} \Phi_D^C(x), \quad (77)$$

and rewrite the partition function in the form

$$Z = \frac{Z_0}{Z_0^\Phi} \int [D\Phi] \exp \{S_{eff}[\Phi]\} \quad (78)$$

with the effective action

$$S_{eff}[\Phi] = -\frac{1}{2} \int dx \Phi_B^A(x) U_{AC}^{BD} \Phi_D^C(x) + W[\Delta], \quad (79)$$

$$\exp \{W[\Delta]\} = 1 + \sum_{n=1}^{\infty} \Gamma^{(n)}[\Delta] = \left\langle T \left[ \exp \left\{ - \int dx \Delta_A^B(x) \bar{\psi}^A(x) \psi_B(x) \right\} \right] \right\rangle. \quad (80)$$

Calculations give

$$W[\Delta] = \sum_{n=1}^{\infty} W^{(n)}[\Delta], \quad (81)$$

$$W^{(1)}[\Delta] = \int dx \Delta_A^B(x) S_B^A(0), \quad (82)$$

$$W^{(2)}[\Delta] = -\frac{1}{2} \int dx_1 \int dx_2 \Delta_{A_1}^{B_1}(x_1) S_{B_1}^{A_2}(x_1 - x_2) \Delta_{A_2}^{B_2}(x_2) S_{B_2}^{A_1}(x_2 - x_1), \quad (83)$$

$$\begin{aligned} W^{(3)}[\Delta] &= \frac{1}{3} \int dx_1 \dots \int dx_3 \Delta_{A_1}^{B_1}(x_1) S_{B_1}^{A_2}(x_1 - x_2) \Delta_{A_2}^{B_2}(x_2) \\ &\quad S_{B_2}^{A_3}(x_2 - x_3) \Delta_{A_3}^{B_3}(x_3) S_{B_3}^{A_1}(x_3 - x_1), \end{aligned} \quad (84)$$

.....

$$\begin{aligned} W^{(n)}[\Delta] &= \frac{(-1)^{n+1}}{n} \int dx_1 \dots \int dx_n \Delta_{A_1}^{B_1}(x_1) S_{B_1}^{A_2}(x_1 - x_2) \Delta_{A_2}^{B_2}(x_2) \\ &\quad S_{B_2}^{A_3}(x_2 - x_3) \dots \Delta_{A_n}^{B_n}(x_n) S_{B_n}^{A_1}(x_n - x_1). \end{aligned} \quad (85)$$

From the variational principle

$$\frac{\delta S_{eff}(\Phi)}{\delta \Phi_D^C(x)} = 0 \quad (86)$$

we derive the field equation

$$\Delta_C^D(x) = U_{CA}^{DB} \frac{\delta W[\Delta]}{\delta \Delta_A^B(x)} = U_{CA}^{DB} \mathbf{S}_B^A(x, x), \quad (87)$$

where  $\mathbf{S}_B^A(y, x)$  is the two-point Green function of the quark field in the presence of the pairing interaction

$$\begin{aligned} \mathbf{S}_B^A(y, x) &= S_B^A(y - x) - \int dx_1 S_B^{A_1}(y - x_1) \Delta_{A_1}^{B_1}(x_1) S_{B_1}^A(x_1 - x) \\ &\quad + \int dx_1 \int dx_2 S_B^{A_1}(y - x_1) \Delta_{A_1}^{B_1}(x_1) S_{B_1}^{A_2}(x_1 - x_2) \Delta_{A_2}^{B_2}(x_2) S_{B_2}^A(x_2 - x) \\ &\quad - \int dx_1 \dots \int dx_3 S_B^{A_1}(y - x_1) \Delta_{A_1}^{B_1}(x_1) S_{B_1}^{A_2}(x_1 - x_2) \Delta_{A_2}^{B_2}(x_2) \\ &\quad S_{B_2}^{A_3}(x_2 - x_3) \Delta_{A_3}^{B_3}(x_3) S_{B_3}^A(x_3 - x) + \dots. \end{aligned} \quad (88)$$

It satisfies the Schwinger-Dyson equation

$$\mathbf{S}_B^A(y, x) = S_B^A(y - x) - \int dz S_B^C(y - z) \Delta_C^D(z) \mathbf{S}_D^A(z, x). \quad (89)$$

In the special class of the constant solutions of the field equation (87)

$$\Delta_B^A(x) = \Delta_B^A = \text{const} \quad (90)$$

$\mathbf{S}_B^A(y, x)$  depends only on the coordinate difference

$$\mathbf{S}_B^A(y, x) = \mathbf{S}_B^A(y - x). \quad (91)$$

For its Fourier transform we have then an algebraic equation. Denote  $\Delta$  the matrix with the elements  $\Delta_A^B$ . From the equation (89) it follows that

$$\tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m) = \tilde{S}(\mathbf{p}, \varepsilon_m) - \tilde{S}(\mathbf{p}, \varepsilon_m) \Delta \tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m) \quad (92)$$

and

$$\frac{1}{\tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m)} = \frac{1}{\tilde{S}(\mathbf{p}, \varepsilon_m)} + \Delta. \quad (93)$$

With the field satisfying the equation (87) the effective action equals

$$\begin{aligned}
S_{eff}[\Phi] &= W[\Delta] - \frac{1}{2} \int dx \Delta_A^B(x) \frac{\delta W[\Delta]}{\delta \Delta_A^B(x)} = \left(1 - \frac{1}{2}\right) \int dx \Delta_A^B(x) S_B^A(0) \\
&\quad + \left(\frac{1}{3} - \frac{1}{2}\right) \int dx_1 \int dx_2 \int dx_3 \Delta_{A_1}^{B_1}(x_1) S_{B_1}^{A_2}(x_1 - x_2) \Delta_{A_2}^{B_2}(x_2) \\
&\quad S_{B_2}^{A_3}(x_2 - x_3) \Delta_{A_3}^{B_3}(x_3) S_{B_3}^{A_1}(x_3 - x_1) \\
&\quad - \left(\frac{1}{4} - \frac{1}{2}\right) \int dx_1 \dots \int dx_4 \Delta_{A_1}^{B_1}(x_1) S_{B_1}^{A_2}(x_1 - x_2) \Delta_{A_2}^{B_2}(x_2) \\
&\quad S_{B_2}^{A_3}(x_2 - x_3) \dots \Delta_{A_4}^{B_4}(x_4) S_{B_4}^{A_1}(x_4 - x_1) + \dots \\
&= \text{Tr} \left\{ \left(1 - \frac{1}{2}\right) \int dx \Delta(x) S(0) \right. \\
&\quad + \left(\frac{1}{3} - \frac{1}{2}\right) \int dx_1 \int dx_2 \int dx_3 \Delta(x_1) S(x_1 - x_2) \\
&\quad \Delta(x_2) S(x_2 - x_3) \Delta(x_3) S(x_3 - x_1) \\
&\quad - \left(\frac{1}{4} - \frac{1}{2}\right) \int dx_1 \dots \int dx_4 \Delta(x_1) S(x_1 - x_2) \Delta(x_2) \\
&\quad S(x_2 - x_3) \dots \Delta(x_4) S(x_4 - x_1) + \dots \\
&\quad \left. \right\},
\end{aligned} \tag{94}$$

where  $\Delta(x)$  is the matrix with elements  $\Delta_A^B(x)$ . It follows that in the case of the constant solutions (90) of the field equations (87) we have following formula determining the free energy density  $F[\mathbf{x}; \Delta]$ :

$$\begin{aligned}
F[\mathbf{x}; \Delta] &= F[\Delta] = \left(1 - \frac{1}{2}\right) \Delta_A^B S_B^A(0) \\
&\quad + \left(\frac{1}{3} - \frac{1}{2}\right) \int dy \int dz \Delta_A^B S_B^C(x - y) \Delta_C^D S_D^E(y - z) \Delta_E^F S_F^A(z - x) \\
&\quad - \left(\frac{1}{4} - \frac{1}{2}\right) \int dy \int dz \int dw \Delta_A^B S_B^C(x - y) \Delta_C^D S_D^E(y - z) \\
&\quad \Delta_E^F S_F^G(z - w) \Delta_G^H S_H^A(w - x) + \dots \\
&= \text{Tr} \left\{ \left(1 - \frac{1}{2}\right) \Delta S(0) \right. \\
&\quad + \left(\frac{1}{3} - \frac{1}{2}\right) \Delta \int dy \int dz S(x - y) \Delta S(y - z) \Delta S(z - x) \\
&\quad - \left(\frac{1}{4} - \frac{1}{2}\right) \Delta \int dy \int dz \int dw S(x - y) \Delta S(y - z) \\
&\quad \Delta S(z - w) \Delta S(w - x) + \dots \\
&\quad \left. \right\} \\
&= \frac{1}{\beta} \sum_m \frac{1}{(2\pi)^3} \int d\mathbf{p} \text{Tr} \left\{ \left(1 - \frac{1}{2}\right) \Delta \tilde{S}(\mathbf{p}, \varepsilon_m) \right. \\
&\quad \left. + \left(\frac{1}{3} - \frac{1}{2}\right) [\Delta \tilde{S}(\mathbf{p}, \varepsilon_m)]^3 - \left(\frac{1}{4} - \frac{1}{2}\right) [\Delta \tilde{S}(\mathbf{p}, \varepsilon_m)]^4 + \dots \right\}.
\end{aligned} \tag{95}$$

Summing up the infinite series, we obtain

$$F[\Delta] = \frac{1}{\beta} \sum_m \frac{1}{(2\pi)^3} \int d\mathbf{p} \text{Tr} \left\{ \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \left[ \int_0^1 \tilde{\mathbf{S}}^\xi(\mathbf{p}, \varepsilon_m) d\xi - \frac{1}{2} \tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m) \right] \right\}, \tag{96}$$

where  $\tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m)$  satisfies the equation (93) and  $\tilde{\mathbf{S}}^\xi(\mathbf{p}, \varepsilon_m)$  is determined by a similar one with the replacement of  $\Delta$  by  $\xi\Delta$ :

$$\frac{1}{\tilde{\mathbf{S}}^\xi(\mathbf{p}, \varepsilon_m)} = \frac{1}{\tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m)} + \xi\Delta. \tag{97}$$

The order parameters  $\Delta_A^B$  have the form

$$\Delta_A^B = \Delta_{(ai\alpha)}^{(bj\beta)} = \delta_\alpha^\beta \Delta_{(ai)}^{S(bj)} + (\gamma_5)_\alpha^\beta \Delta_{(ai)}^{P(bj)}. \quad (98)$$

The non-vanishing order parameters  $\Delta_{(ai)}^{P(bj)}$  lowering the free energy would mean the spontaneous parity conservation violation. If  $M = 0$  and the interaction Lagrangian (104) is invariant under the chiral transformations, then the existence of non-vanishing order parameters  $\Delta_{(ai)}^{S(bj)}$  and/or  $\Delta_{(ai)}^{P(bj)}$  lowering the free energy would signify the spontaneous breaking of the chiral invariance. If  $\Delta_{(ai)}^{S(bj)}$  and/or  $\Delta_{(ai)}^{P(bj)}$  are not the singlets of the color and/or flavor group, then the color and/or flavor symmetries are spontaneously broken. For the system with the isomorphic color and flavor groups  $SU(N)_c$  and  $SU(N)_f$  there may exist the superconducting order parameters which are the irreducible spinor representations of the groups  $SU(N)_c$  and  $SU(N)_f$  but the singlet of the the "diagonal"  $SU(N)$  subgroup of the direct product  $SU(N)_c \otimes SU(N)_f$ . In this case we have the "color-flavor locking".

Now we consider the quark-antiquark pairing generated by the effective non-local interaction of the quark fields due to the gluon exchange. For this purpose we rewrite the partition function (42) in the appropriate form

$$Z = \int [D\psi] [D\bar{\psi}] \exp \left\{ - \int dx \bar{\psi}^A(x) L_A^B \psi_B(x) \right\} \exp \left\{ \frac{1}{2} \int dx \int dy \bar{\psi}^A(x) \psi_B(y) U_{AC}^{BD}(x-y) \bar{\psi}^C(y) \psi_D(x) \right\}. \quad (99)$$

with the new notations

$$U_{AC}^{BD}(x-y) = -V_{AC}^{DB}(x-y), \quad (100)$$

$V_{AC}^{DB}(x-y)$  being given in the formula (43). Introduce the hermitian bi-local bosonic fields  $\Phi_B^A(x, y)$  and the functional integral

$$Z_0^\Phi = \int [D\Phi] \exp \left\{ -\frac{1}{2} \int dx \int dy \Phi_B^A(x, y) U_{AC}^{BD}(x-y) \Phi_D^C(y, x) \right\}. \quad (101)$$

By shifting the functional integration variables, we obtain

$$\begin{aligned} & \exp \left\{ \frac{1}{2} \int dx \int dy \bar{\psi}^A(x) \psi_B(y) U_{AC}^{BD}(x-y) \bar{\psi}^C(y) \psi_D(x) \right\} = \\ & = \frac{1}{Z_0^\Phi} \int [D\Phi] \exp \left\{ -\frac{1}{2} \int dx \int dy \Phi_B^A(x, y) U_{AC}^{BD}(x-y) \Phi_D^C(y, x) \right\} \\ & \quad \exp \left\{ - \int dx \int dy \bar{\psi}^A(x) \psi_B(y) \Delta_A^B(x, y) \right\}, \end{aligned} \quad (102)$$

where

$$\Delta_A^B(x, y) = U_{AC}^{BD}(x-y) \Phi_D^C(y, x), \quad (103)$$

and rewrite the partition function in the form (78) with the effective action

$$S_{\text{eff}}[\Phi] = -\frac{1}{2} \int dx \int dy \Phi_B^A(x, y) U_{AC}^{BD}(x-y) \Phi_D^C(y, x) + W[\Delta], \quad (104)$$

$$\begin{aligned} \exp \{W[\Delta]\} &= 1 + \sum_{n=1}^{\infty} \Gamma^{(n)}[\Delta] \\ &= \left\langle T \left[ \exp \left\{ - \int dx \int dy \bar{\psi}^A(x) \psi_B(y) \Delta_A^B(x, y) \right\} \right] \right\rangle. \end{aligned} \quad (105)$$

Calculations give

$$\Gamma^{(1)}[\Delta] = W^{(1)}[\Delta] = \int dx \int dy \Delta_A^B(x, y) S_R^A(y-x), \quad (106)$$

$$\Gamma^{(2)} [\Delta] = \frac{1}{2} \left( W^{(1)} [\Delta] \right)^2 + W^{(2)} [\Delta], \quad (107)$$

$$\begin{aligned} W^{(2)} [\Delta] &= -\frac{1}{2} \int dx_1 \int dy_1 \int dx_2 \int dy_2 \Delta_{A_1}^{B_1} (x_1, y_1) S_{B_1}^{A_2} (y_1 - x_2) \\ &\quad \Delta_{A_2}^{B_2} (x_2, y_2) S_{B_2}^{A_1} (y_2 - x_1), \end{aligned} \quad (108)$$

$$\Gamma^{(3)} [\Delta] = \frac{1}{3!} \left( W^{(1)} [\Delta] \right)^3 + W^{(1)} [\Delta] W^{(2)} [\Delta] + W^{(3)} [\Delta], \quad (109)$$

$$\begin{aligned} W^{(3)} [\Delta] &= \frac{1}{3} \int dx_1 \int dy_1 \dots \int dx_3 \int dy_3 \Delta_{A_1}^{B_1} (x_1, y_1) S_{B_1}^{A_2} (y_1 - x_2) \\ &\quad \Delta_{A_2}^{B_2} (x_2, y_2) S_{B_2}^{A_3} (y_2 - x_3) \Delta_{A_3}^{B_3} (x_3, y_3) S_{B_3}^{A_1} (y_3 - x_1), \quad (110) \\ &\quad \dots \dots \dots \end{aligned}$$

The field equation is derived from the variational principle

$$\frac{\delta S_{\text{eff}} [\Phi]}{\delta \Phi_D^C (y, x)} = 0 \quad (111)$$

and has the form

$$\Delta_C^D (y, x) = U_{CA}^{DB} (x - y) \frac{\delta W [\Delta]}{\delta \Delta_A^B (x, y)}. \quad (112)$$

Using the expressions for  $W^{(n)} [\Delta]$ , we obtain the explicit equation

$$\begin{aligned} \Delta_C^D (y, x) &= U_{CA}^{DB} (x - y) \{ S_B^A (y - x) \\ &\quad - \int dx_2 \int dy_2 S_B^{A_2} (y - x_2) \Delta_{A_2}^{B_2} (x_2, y_2) S_{B_2}^A (y_2 - x) \\ &\quad + \int dx_2 \int dy_2 \int dx_3 \int dy_3 S_B^{A_2} (y - x_2) \Delta_{A_2}^{B_2} (x_2, y_2) \\ &\quad S_{B_2}^{A_3} (y_2 - x_3) \Delta_{A_3}^{B_3} (x_3, y_3) S_{B_3}^A (y_3 - x) \\ &\quad + \dots \dots \dots \} . \end{aligned} \quad (113)$$

Introduce the two-point Green function of quark field in the presence of the quark-antiquark pairing

$$\begin{aligned} \mathbf{S}_B^A (y, x) &= S_B^A (y - x) - \int dx_2 \int dy_2 S_B^{A_2} (y - x_2) \Delta_{A_2}^{B_2} (x_2, y_2) S_{B_2}^A (y_2 - x) \\ &\quad + \int dx_2 \int dy_2 \int dx_3 \int dy_3 S_B^{A_2} (y - x_2) \Delta_{A_2}^{B_2} (x_2, y_2) S_{B_2}^{A_3} (y_2 - x_3) \\ &\quad \Delta_{A_3}^{B_3} (x_3, y_3) S_{B_3}^A (y_3 - x) + \dots \end{aligned} \quad (114)$$

It satisfies the Schwinger-Dyson equation

$$\mathbf{S}_B^A (y, x) = S_B^A (y - x) - \int dz \int dw S_B^C (y - z) \Delta_C^D (z, w) \mathbf{S}_D^A (w, x). \quad (115)$$

Then the field equation (113) becomes

$$\Delta_C^D (y, x) = U_{CA}^{DB} (x - y) \mathbf{S}_B^A (y, x). \quad (116)$$

Consider the solution of this field equation in the special class of functions depending only on the difference of the coordinates

$$\Delta_A^B (x, y) = \Delta_A^B (x - y). \quad (117)$$

In this case the function  $\mathbf{S}_B^A (x, y)$  depends also only on the difference of the coordinates

$$\mathbf{S}_B^A (x, y) = \mathbf{S}_B^A (x - y) \quad (118)$$

Performing the Fourier transformation

$$\Delta_A^B(\mathbf{x} - \mathbf{y}, \tau - \sigma) = \frac{1}{\beta} \sum_m e^{i\varepsilon_m(\tau - \sigma)} \frac{1}{(2\pi)^3} \int d\mathbf{p} e^{i\mathbf{p}(\mathbf{x} - \mathbf{y})} \tilde{\Delta}_A^B(\mathbf{p}, \varepsilon_m), \quad (119)$$

$$\varepsilon_m = (2m + 1) \frac{\pi}{\beta},$$

and introducing the matrices  $\tilde{\Delta}(\mathbf{p}, \varepsilon_m)$  with the elements  $\tilde{\Delta}_A^B(\mathbf{p}, \varepsilon_m)$ , we rewrite the integral relation (114) and the integral equation (115) in the form of the algebraic ones:

$$\begin{aligned} \tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m) &= \tilde{S}(\mathbf{p}, \varepsilon_m) - \tilde{S}(\mathbf{p}, \varepsilon_m) \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}(\mathbf{p}, \varepsilon_m) \\ &\quad + \tilde{S}(\mathbf{p}, \varepsilon_m) \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}(\mathbf{p}, \varepsilon_m) \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}(\mathbf{p}, \varepsilon_m) \dots \end{aligned} \quad (120)$$

and

$$\tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m) = \tilde{S}(\mathbf{p}, \varepsilon_m) - \tilde{S}(\mathbf{p}, \varepsilon_m) \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m) \quad (121)$$

or

$$\frac{1}{\tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m)} = \frac{1}{\tilde{S}(\mathbf{p}, \varepsilon_m)} + \tilde{\Delta}(\mathbf{p}, \varepsilon_m). \quad (122)$$

The field equation (116) becomes

$$\tilde{\Delta}_C^D(\mathbf{p}, \varepsilon_m) = \frac{1}{\beta} \sum_n \frac{1}{(2\pi)^3} \int d\mathbf{q} \tilde{U}_{CA}^{DB}(\mathbf{p} - \mathbf{q}, \varepsilon_m - \varepsilon_n) \tilde{\mathbf{S}}_B^A(\mathbf{q}, \varepsilon_n) \quad (123)$$

where  $\tilde{U}_{CA}^{DB}(\mathbf{p} - \mathbf{q}, \varepsilon_m - \varepsilon_n)$  is the Fourier transform of  $U_{CA}^{DB}(x - y)$ ,

$$\begin{aligned} U_{CA}^{DB}(\mathbf{x} - \mathbf{y}, \tau - \sigma) &= \frac{1}{\beta} \sum_m e^{i\omega_m(\sigma - \tau)} \frac{1}{(2\pi)^3} \int d\mathbf{p} e^{i\mathbf{p}(\mathbf{y} - \mathbf{x})} \tilde{U}_{CA}^{DB}(\mathbf{p}, \omega_m), \\ \omega_m &= 2m \frac{\pi}{\beta}. \end{aligned} \quad (124)$$

Using the field equation (112), we obtain the value of the effective action (104)

$$\begin{aligned} S_{eff}[\Phi] &= W[\Delta] - \frac{1}{2} \int dx \int dy \Delta_A^B(x, y) \frac{\delta W[\Delta]}{\delta \Delta_A^B(x, y)} \\ &= \left(1 - \frac{1}{2}\right) \int dx \int dy \Delta_A^B(x, y) S_B^A(y - x) \\ &\quad + \left(\frac{1}{3} - \frac{1}{2}\right) \int dx_1 \int dy_1 \dots \int dx_3 \int dy_3 \Delta_{A_1}^{B_1}(x_1, y_1) S_{B_1}^{A_2}(y_1 - x_2) \\ &\quad \Delta_{A_2}^{B_2}(x_2, y_2) S_{B_2}^{A_3}(y_2 - x_3) \Delta_{A_3}^{B_3}(x_3, y_3) S_{B_3}^{A_1}(y_3 - x_1) \\ &\quad - \left(\frac{1}{4} - \frac{1}{2}\right) \int dx_1 \int dy_1 \dots \int dx_4 \int dy_4 \Delta_{A_1}^{B_1}(x_1, y_1) S_{B_1}^{A_2}(y_1 - x_2) \\ &\quad \Delta_{A_2}^{B_2}(x_2, y_2) \dots \Delta_{A_4}^{B_4}(x_4, y_4) S_{B_4}^{A_1}(y_4 - x_1) \\ &\quad + \dots \\ &= \text{Tr} \left\{ \left(1 - \frac{1}{2}\right) \int dx \int dy \Delta(x, y) S(y - x) \right. \\ &\quad + \left(\frac{1}{3} - \frac{1}{2}\right) \int dx_1 \int dy_1 \dots \int dx_3 \int dy_3 \Delta(x_1, y_1) S(y_1 - x_2) \\ &\quad \Delta(x_2, y_2) S(y_2 - x_3) \Delta(x_3, y_3) S(y_3 - x_1) \\ &\quad - \left(\frac{1}{4} - \frac{1}{2}\right) \int dx_1 \int dy_1 \dots \int dx_4 \int dy_4 \Delta(x_1, y_1) S(y_1 - x_2) \\ &\quad \Delta(x_2, y_2) \dots \Delta(x_4, y_4) S(y_4 - x_1) + \dots \left. \right\}, \end{aligned} \quad (125)$$

where  $\Delta(x, y)$  is the matrix with the elements  $\Delta_A^B(x, y)$ . For the fields in the special class (117) the effective action is expressed in terms of the free energy density  $F[\mathbf{x}; \Delta]$

$$S_{eff}[\Phi] = -\beta \int d\mathbf{x} F[\mathbf{x}; \Delta]. \quad (126)$$

It follows that

$$\begin{aligned}
F[\mathbf{x}; \Delta] &= F[\Delta] = \\
&= \left(1 - \frac{1}{2}\right) \int dy \Delta_A^B(x-y) S_B^A(y-x) \\
&\quad + \left(\frac{1}{3} - \frac{1}{2}\right) \int dy \int dx_2 \int dy_2 \int dx_3 \int dy_3 \Delta_{A_1}^{B_1}(x-y_1) S_{B_1}^{A_2}(y_1-x_2) \\
&\quad \Delta_{A_2}^{B_2}(x_2-y_2) S_{B_2}^{A_3}(y_2-x_3) \Delta_{A_3}^{B_3}(x_3-y_3) S_{B_3}^{A_1}(y_3-x) \\
&\quad - \left(\frac{1}{4} - \frac{1}{2}\right) \int dy \int dx_2 \int dy_2 \dots \int dx_4 \int dy_4 \Delta_{A_1}^{B_1}(x-y_1) S_{B_1}^{A_2}(y_1-x_2) \\
&\quad \Delta_{A_2}^{B_2}(x_2-y_2) \dots S_{B_3}^{A_4}(y_3-x_4) \Delta_{A_4}^{B_4}(x_4-y_4) S_{B_4}^{A_1}(y_4-x) \\
&\quad + \dots \\
&= \text{Tr} \left\{ \left(1 - \frac{1}{2}\right) \int dy \Delta(x-y) S(y-x) \right. \\
&\quad + \left(\frac{1}{3} - \frac{1}{2}\right) \int dy \int dx_2 \int dy_2 \int dx_3 \int dy_3 \Delta(x-y_1) S(y_1-x_2) \\
&\quad \Delta(x_2-y_2) S(y_2-x_3) \Delta(x_3-y_3) S(y_3-x) \\
&\quad - \left(\frac{1}{4} - \frac{1}{2}\right) \int dy \int dx_2 \int dy_2 \dots \int dx_4 \int dy_4 \Delta(x-y_1) S(y_1-x_2) \\
&\quad \Delta(x_2-y_2) \dots S(y_3-x_4) \Delta(x_4-y_4) S(y_4-x) + \dots \left. \right\} \quad (127) \\
&= \frac{1}{\beta} \sum_m \frac{1}{(2\pi)^3} \int d\mathbf{p} \text{Tr} \left\{ \left(1 - \frac{1}{2}\right) \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}(\mathbf{p}, \varepsilon_m) \right. \\
&\quad + \left(\frac{1}{3} - \frac{1}{2}\right) \left[ \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}(\mathbf{p}, \varepsilon_m) \right]^3 \\
&\quad - \left(\frac{1}{4} - \frac{1}{2}\right) \left[ \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \tilde{S}(\mathbf{p}, \varepsilon_m) \right]^4 + \dots \left. \right\}.
\end{aligned}$$

Summing up the infinite series, we obtain

$$F[\Delta] = \frac{1}{\beta} \sum_m \frac{1}{(2\pi)^3} \int d\mathbf{p} \text{Tr} \left\{ \tilde{\Delta}(\mathbf{p}, \varepsilon_m) \left[ \int_0^1 \tilde{\mathbf{S}}^\xi(\mathbf{p}, \varepsilon_m) d\xi - \frac{1}{2} \tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m) \right] \right\}, \quad (128)$$

where  $\tilde{\mathbf{S}}^\xi(\mathbf{p}, \varepsilon_m)$  is determined by the equation of the form (122) with the replacement of  $\tilde{\Delta}(\mathbf{p}, \varepsilon_m)$  by  $\xi \tilde{\Delta}(\mathbf{p}, \varepsilon_m)$

$$\frac{1}{\tilde{\mathbf{S}}^\xi(\mathbf{p}, \varepsilon_m)} = \frac{1}{\tilde{\mathbf{S}}(\mathbf{p}, \varepsilon_m)} + \xi \tilde{\Delta}(\mathbf{p}, \varepsilon_m). \quad (129)$$

Introduce 4-vector  $p_\mu$  with  $p_4 = \varepsilon_m$  and denote  $\tilde{\Delta}_A^B(\mathbf{p}, \varepsilon_m)$  by  $\tilde{\Delta}_A^B(p)$ . These order parameters have following most general form

$$\begin{aligned}
\tilde{\Delta}_A^B(p) &= \delta_\alpha^\beta \tilde{\Delta}_{(ai)}^{S(bj)}(p) + (\gamma_5)_\alpha^\beta \tilde{\Delta}_{(ai)}^{P(bj)}(p) + (\gamma_\mu)_\alpha^\beta \tilde{\Delta}_{\mu(ai)}^{V(bj)}(p) \\
&\quad + (\gamma_\mu \gamma_5)_\alpha^\beta \tilde{\Delta}_{\mu(ai)}^{A(bj)}(p) + (\sigma_{\mu\nu})_\alpha^\beta \tilde{\Delta}_{\mu\nu(ai)}^{t(bj)}(p)
\end{aligned} \quad (130)$$

The existence of the non-vanishing order parameters with definite transformation properties would mean the spontaneous breaking of the corresponding symmetries.

## 4 Formation of triquarks

It is straightforward to generalize the method presented in preceding Sections for applying to the problem of the formation of triquarks - the bound states of three quarks. We note that the fundamental interaction mechanisms in QCD (instanton

induced, gluon exchange, etc...) always lead to some effective (non-local, in general) six-fermion interaction between quark fields with the effective interaction action of the general form

$$\begin{aligned} S_{\text{int}} &= \frac{1}{6} \int dx \int dy \int dz \int du \int dv \int dw \bar{\psi}^F(w) \bar{\psi}^E(v) \bar{\psi}^D(u) \\ &\quad V_{DEF}^{CBA}(u, v, w; z, y, x) \psi_A(x) \psi_B(y) \psi_C(z), \\ V_{DEF}^{CBA}(u, v, w; z, y, x) &= -V_{DEF}^{CAB}(u, v, w; z, y, x) = -V_{EDF}^{CBA}(u, v, w; z, y, x) = \dots \end{aligned} \quad (131)$$

The form-factors  $V_{DEF}^{CBA}(u, v, w; z, y, x)$  depend only on the differences of the space-time coordinates. The partition function of the many-quark system with this effective six-quark interaction equals

$$\begin{aligned} Z &= \int [D\psi] [D\bar{\psi}] \exp \left\{ - \int dx \bar{\psi}^A(x) L_A^B \psi_B(x) \right\} \\ &\quad \exp \left\{ \frac{1}{6} \int dx \int dy \int dz \int du \int dv \int dw \bar{\psi}^F(w) \bar{\psi}^E(v) \bar{\psi}^D(u) \right. \\ &\quad \left. V_{DEF}^{CBA}(u, v, w; z, y, x) \psi_A(x) \psi_B(y) \psi_C(z) \right\}. \end{aligned} \quad (132)$$

In order to describe the triquarks we introduce some tri-spinor tri-local field  $\Phi_{ABC}(x, y, z)$  as well as its conjugate  $\bar{\Phi}^{CBA}(z, y, x)$  and set

$$\begin{aligned} Z_0^\Phi &= \int [D\Phi] [D\bar{\Phi}] \exp \left\{ \frac{1}{6} \int dx \int dy \int dz \int du \int dv \int dw \right. \\ &\quad \left. \bar{\Phi}^{FED}(w, v, u) V_{DEF}^{CBA}(u, v, w; z, y, x) \Phi_{ABC}(x, y, z) \right\}. \end{aligned} \quad (133)$$

By shifting the functional integration variables

$$\begin{aligned} \Phi_{ABC}(x, y, z) &\rightarrow \Phi_{ABC}(x, y, z) + \frac{1}{\sqrt{2}} \psi_A(x) \psi_B(y) \psi_C(z), \\ \bar{\Phi}^{FED}(w, v, u) &\rightarrow \bar{\Phi}^{FED}(w, v, u) + \frac{1}{\sqrt{2}} \bar{\psi}^F(w) \bar{\psi}^E(v) \bar{\psi}^D(u), \end{aligned}$$

we establish the Hubbard-Stratonovich transformation

$$\begin{aligned} &\exp \left\{ \frac{1}{6} \int dx \int dy \int dz \int du \int dv \int dw \bar{\psi}^F(w) \bar{\psi}^E(v) \bar{\psi}^D(u) \right. \\ &\quad \left. V_{DEF}^{CBA}(u, v, w; z, y, x) \psi_A(x) \psi_B(y) \psi_C(z) \right\} \\ &= \frac{1}{Z_0^\Phi} \int [D\Phi] [D\bar{\Phi}] \exp \left\{ -\frac{1}{3} \int dx \int dy \int dz \int du \int dv \int dw \right. \\ &\quad \left. \bar{\Phi}^{FED}(w, v, u) V_{DEF}^{CBA}(u, v, w; z, y, x) \Phi_{ABC}(x, y, z) \right\} \\ &\quad \exp \left\{ -\frac{1}{\sqrt{18}} \int dx \int dy \int dz \left[ \bar{\Delta}^{CBA}(z, y, x) \psi_A(x) \psi_B(y) \psi_C(x) \right. \right. \\ &\quad \left. \left. + \bar{\psi}^C(z) \bar{\psi}^B(y) \bar{\psi}^A(x) \Delta_{ABC}(x, y, z) \right] \right\}, \end{aligned} \quad (134)$$

where

$$\bar{\Delta}^{CBA}(z, y, x) = \int du \int dv \int dw \bar{\psi}^F(w) \bar{\psi}^E(v) \bar{\psi}^D(u) V_{DEF}^{CBA}(u, v, w; z, y, x), \quad (135)$$

$$\Delta_{ABC}(x, y, z) = \int du \int dv \int dw V_{DEF}^{CBA}(u, v, w; z, y, x) \psi_D(u) \psi_E(v) \psi_F(w),$$

and transform, after lengthy calculations, the partition function (132) into the form (23) of a functional integral over the tri-local fields  $\Phi_{ABC}(x, y, z)$  and  $\overline{\Phi}^{CBA}(z, y, x)$  with the effective action

$$S_{\text{eff}}[\Phi, \overline{\Phi}] = -\frac{1}{3} \int dx \int dy \int dz \overline{\Phi}^{FDE}(w, v, u) V_{DEF}^{CBA}(u, v, w; z, y, x) \Phi_{ABC}(x, y, z) + W[\Delta, \overline{\Delta}] \quad (136)$$

and the functional  $W[\Delta, \overline{\Delta}]$  of the form

$$W[\Delta, \overline{\Delta}] = \sum_{n=1}^{\infty} W^{(2n)}[\Delta, \overline{\Delta}], \quad (137)$$

where  $W^{(2n)}[\Delta, \overline{\Delta}]$  is a functional of the  $n$ -th order with respect to each type of tri-local fields  $\Delta_{ABC}(x, y, z)$  and  $\overline{\Delta}^{CBA}(z, y, x)$ , for example

$$W^{(2)}[\Delta, \overline{\Delta}] = \frac{1}{3} \int dx \int dy \int dz \int du \int dv \int dw \overline{\Delta}^{FED}(w, v, u) S_F^C(w - z) S_E^B(v - y) S_D^A(u - x) \Delta_{ABC}(x, y, z), \quad (138)$$

$$\begin{aligned} W^{(4)}[\Delta, \overline{\Delta}] = & -\frac{1}{2} \int dx_1 \int dy_1 \int dz_1 \dots \int du_2 \int dv_2 \int dw_2 \overline{\Delta}^{F_1 E_1 D_1}(w_1, v_1, u_1) \\ & \overline{\Delta}^{F_2 E_2 D_2}(w_2, v_2, u_2) S_{F_2}^{C_1}(w_2 - z_1) S_{E_1}^{B_1}(v_1 - y_1) S_{D_2}^{A_1}(u_1 - x_1) S_{F_1}^{C_2}(w_1 - z_2) \\ & S_{E_2}^{B_2}(v_2 - y_2) S_{D_2}^{A_2}(u_2 - x_2) \Delta_{A_2 B_2 C_2}(x_2, y_2, z_2) \Delta_{A_1 B_1 C_1}(x_1, y_1, z_1) \\ & \dots \end{aligned} \quad (139)$$

From the variational principle we derive the field equation

$$\frac{1}{3} \Delta_{ABC}(x, y, z) = \int du \int dv \int dw V_{ABC}^{FED}(u, v, w; z, y, x) \sum_{n=1}^{\infty} \frac{\delta W^{(n)}[\Delta, \overline{\Delta}]}{\delta \overline{\Delta}^{FED}(w, v, u)}. \quad (140)$$

Using explicit expression of  $W^{(2n)}[\Delta, \overline{\Delta}]$ , we have shown that up to the 6th order of the perturbation theory there exists following system of integral equations

$$\begin{aligned} \Delta_{ABC}(x, y, z) = & \int du \int dv \int dw \int dx' \int dy' \int dz' V_{ABC}^{FED}(u, v, w; z, y, x) \\ & G_F^{C'}(w, z') G_E^{B'}(v, y') G_D^{A'}(u, x') \Delta_{A'B'C'}(x', y', z'), \end{aligned} \quad (141)$$

$$G_A^D(x, u) = S_A^D(x - u) + \int dy \int dz S_A^B(x - y) \Sigma_B^C(y, z) G_C^D(z, u), \quad (142)$$

$$\Sigma_C^F(z, w) = \int dx \int dy \int du \int dv \overline{\Delta}^{FED}(w, v, u) G_D^A(u, x) G_E^B(v, y) \Delta_{ABC}(x, y, z). \quad (143)$$

It is easy to verify that  $G_A^D(x, u)$  is the two-point Green function of the quark field in the presence of its interaction with the "external" tri-local fields  $\Delta_{ABC}(x, y, z)$  and  $\overline{\Delta}^{FED}(w, v, u)$ . It is determined by the Schwinger-Dyson equation represented by the Feynman diagram in Fig. 1. with the self-energy part (143) represented by the Feynman diagram in Fig. 2.

The solutions of the system of integral equations (141)-(143) in the class of the fields depending only on the differences of the coordinates can be considered as

the anticommuting order parameters of the ground state of the many-quark system with the binding of the quarks into the triquarks. This means that in the QCD dense quark matter there might exist a phase transition with the anticommuting order parameters. Note that there is no condensation of the triquarks, because these composite particles are fermions.

## Acknowledgements.

The author would like to express his sincere appreciation to the National Natural Sciences Council of Vietnam for the support to this work.

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